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Chapter 9

THE TONGA AND KERMADEC RIDGES

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I. INTRODUCTION

A. History

The 150 islands forming the Kingdom of Tonga seem to have been sought unconsciously by daring navigators. Uninhabited, they were first visited and settled during Polynesian ocean migrations four or five centuries before the Christian era, and it was only 2000 years later that they were discovered afresh by the first European voyagers.

Now, as the 20th century comes to a close, a flight of about 48 hours separates old Europe from the soil of Nuku'alofa, the capital of the Kingdom, where can be seen rows of colonial pines mounting guard over the Royal Palace. It is therefore difficult to imagine the courage of the first adventurous navigators and their joy on seeing on the horizon the peaks of the highest volcanoes or the green fringe of coconut palms bordering the coral islands. Nevertheless, the 17th century had scarcely begun when, in 1616, a Dutch vessel commanded by Lemaire and Schouten was the first to sight part of the Tonga archipelago. Following that, ships regularly visited these shores. Tasman stopped there during his voyage from New Zealand to Fiji. The great English navigator, James Cook, made two stops there, in 1773 and 1774, and, delighted by the welcome of the inhabitants, named them the Friendly Islands or archipelago. Toward the end of the 18th century, the French navigator d'Entrecasteaux discovered the Kermadec archipelago, naming it after his second officer, Chevalier Huon de Kermadec, who, already sick, was destined to die shortly afterwards (1793) in New Caledonia.

Other travelers have perhaps seen or landed on the islands, for the archipelago is vast. Can this have been the case for Wallis, Malaspina, or Dumont d'Urville?

Then gradually, beginning in the 19th century, the Kingdom of Tonga entered contemporary history. Now, the ships docking there range from small interisland coasters to passenger ships discharging their loads of tourists and to oceanographic vessels flying the French, American, Japanese, or German flags.

B. Geographic Location

1. *The Tonga and Kermadec Islands*

The islands lie in the South Pacific between 14°30′ and 36°S and between 172°W and 179°E (Fig. 1). The structures from which the Tonga islands emerge are more than 1300 km long and quasilinear, striking north-northeast to south-southwest for about 1000 km. Only at the extremities can a change in orientation be observed. The ridge which forms the base of the Kermadec Islands is also linear for about 1000 km, and is a prolongation of the Tonga ridge (Fig. 2).

The Tonga Kermadec archipelago is only the emergent part of a vast structural

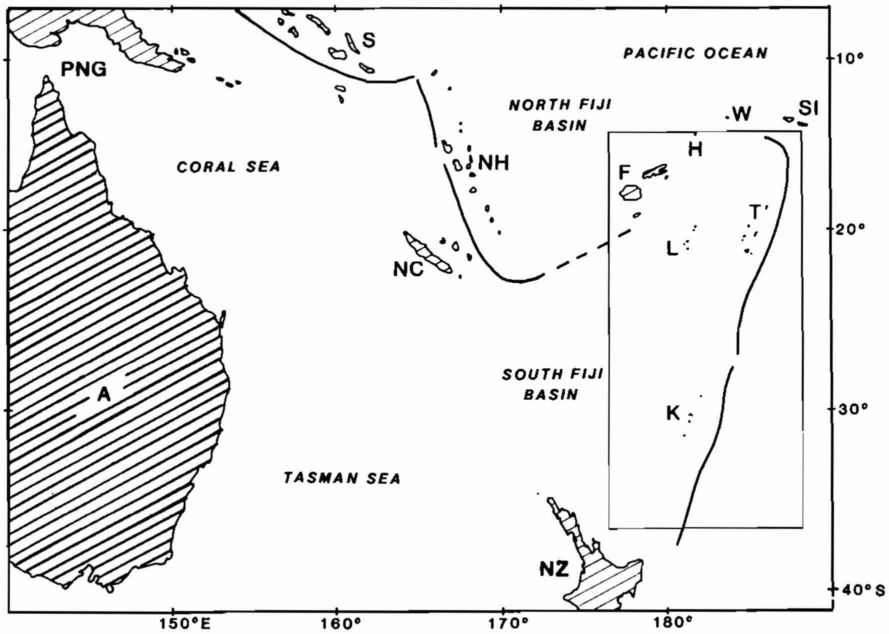

Fig. 1. The geographic location of the Tonga–Kermadec zone in the southwest Pacific. A, Australia; PNG, Papua–New Guinea; S, Solomon; NH, New Hebrides; NC, New Caledonia; F, Fiji; H, Horn (or Futuna); W, Wallis; SI, Samoa; T, Tonga; L, Lau; K, Kermadec; NZ, New Zealand.

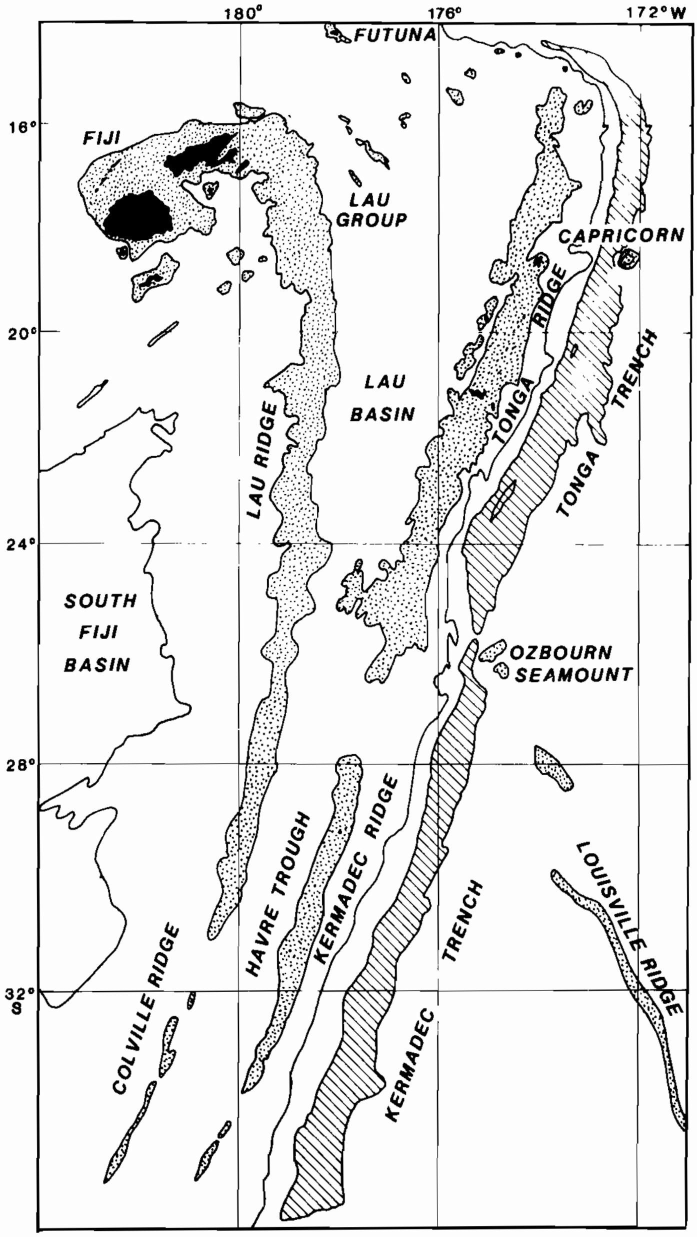

Fig. 2. General map of the Tonga–Kermadec area. The simplified bathymetry of Tonga is drawn from the map of Hawkins (1974), that of Fiji and Kermadec from Mammerickx *et al.* (1971).

edifice which began to take shape prior to the Upper Eocene. This edifice is made up of the following structural elements (from east to west):

- The Tonga–Kermadec trench
- The Tonga–Kermadec ridge
- The Lau basin in the north and the Havre trough to the south
- The Fiji platform and the Lau ridge in the north, and the Colville ridge to the south

Farther to the south, at about 36°S, the Kermadec ridge and trench, the Havre trough, and the Colville ridge terminate, but the Hikurangi trench and the Rotorua volcanic zone of the North Island of New Zealand continue the Tonga–Kermadec structures to the south.

2. *The Tonga Archipelago*

The Kingdom of Tonga consists of about 150 islands, which can be divided into three groups:

- The group of Vava'u in the north
- The group of Ha'apai in the center
- The Tongatapu group in the south, of which the island named is the principal and on which lies the capital, Nuku'alofa

Schematically, the islands lie in two parallel north-northeast to south-southwest trends, of which the eastern contains the largest number and most important of the islands: Tongatapu, Eua, Nomuka, Lifuka, and Vava'u. These are coral islands grown over a volcanic basement, as on Eua, the only island where the volcanic basement has actually been reached below the coral limestone. The western trend is made up of volcanic islands such as Ata, Tofua, Kao, Late, and Fonulaei, some of which still display fumarolic activity. In addition to these islands, there are some reefs formed of ancient eroded volcanoes, such as Falcon, Metis Shoal, Home Reef, and Curacao Reef at the extreme north of the archipelago.

Volcanic activity persists; Falcon Island, since its discovery in 1781, has disappeared and reappeared several times—disappearing most recently in February 1949. An eruption on Curacao Reef occurred in July 1973 and, more recently, in June 1979 a new volcano appeared between Kao and Late. It was named Lateiki in August, and by then its area of 3 hectares was already under attack by the sea. Farther south, a submarine volcano, Monowai, erupted in 1979.

The highest point in the archipelago, with an elevation of 1109 m, is the extinct volcano on Kao. There is, in addition, the volcanic island of Niua Fo'ou which belongs to neither alignment.

3. *The Kermadec Archipelago*

The Kermadec archipelago is formed by a small number of volcanic islands of which the most important, from north to south, are: Raoul, Macaulay, Curtis, Herald, and Esperance. The islands are administered by New Zealand but, with the exception of Raoul on which a meteorological station requires the presence of ten persons, they are uninhabited.

C. Geological Framework

The Tonga–Kermadec region has been studied for many years, for it is a tectonically important zone. This can be well illustrated by reporting the earlier geological and geophysical work and completing it by reference to more recently acquired data (Dupont, 1982a).

Prior to 1800, the only information on the Tonga Islands was contained in navigational reports. Between 1800 and 1900, in addition to descriptions of voyages, there were also descriptions of the volcanoes and some geological observations, of which one dates back to 1811. Between 1900 and 1950, scientific studies multiplied, in geology (Hoffmeister, 1932), in petrography, and in volcanology—all enriching knowledge of these volcanic or coral islands. More specialized studies date from 1950, with works on seismicity (Gutenberg and Richter, 1954), refraction (Raitt *et al.*, 1955), gravity (Talwani *et al.*, 1961), and petrography (Ewart and Bryan, 1973). It was the seismological study on the Tonga–Kermadec island arc which enabled Sykes (1966) and Isacks *et al.* (1968, 1969) to demonstrate the disappearance of oceanic lithosphere in subduction zones.

Geological studies on the whole zone linked tectonically to the Tonga–Kermadec island arc are numerous and can be grouped according to the structure studied.

1. *The Fiji Platform and Lau Ridge*

From the work of Rodda (1967), which was concerned principally with the petrography and tectonics of Fiji (Viti Levu), three broad conclusions can be drawn:

- The oldest volcanic rocks date from the middle Eocene.
- The alternation of volcanic and sedimentary rocks with foraminifera implies alternate periods of emergence and immersion.
- Volcanic activity ended between 5 and 4.7 Ma.

Magnetic and paleomagnetic studies indicate that the Fiji platform has undergone an anticlockwise rotation, although the magnitude of the rotation varies according to author (James and Falvey, 1978; Malahoff *et al.*, 1979). Whatever the magnitude of the rotation of the platform, it can be regarded as an ancient element of the Lau ridge and formerly a continuation of it.

Between 1880 and 1930, the islands on the Lau ridge were studied by Agassiz, Dana, and Davis, who sought in them a perfect example of the evolution of atolls. In 1945, Ladd and Hoffmeister studied the morphology and petrography of the islands which have a volcanic origin and which have undergone numerous vertical movements. Periods of stability have permitted the development of marine terraces now found at a variety of altitudes.

The oldest rocks found on the Lau islands date to between 9 and 6.4 Ma, which does not exclude, for Gill (1976), the possibility of finding Upper Eocene rocks as on Fiji (Viti Levu), for, according to him, the petrographic character of the Fiji platform is the same as that of the Lau ridge.

2. *The Tonga Ridge*

The first important geological work was that of Hoffmeister (1932) on Eua, who showed the existence of a volcanic basement covered by Upper Eocene limestones. It was this work which established a pre-Upper Eocene age for the Tonga island arc.

Later, following the Nova expedition in 1967, basalts were dredged from more than 7000 m, and fresh peridotites and dunites from depths in excess of 9000 m. According to Fisher and Engel (1969), these ultramafic rocks formed the internal wall of the trench. In 1972, Bryan *et al.* pointed out that the activity of the present volcanic line of Tonga was recent, and in the synthesis by Ewart *et al.* (1977) it was recognized that:

- The lavas of Tonga and Kermadec are typical island arc tholeiites.
- The tholeiitic lavas of the Niua Fo'ou volcano, as those of the Lau basin, approximate to those of the oceanic plates.

The first indications of the sedimentary thickness on the Tonga ridge were derived from a combination of drilling and seismic reflection profiling. On Tongatapu, two wells exceeding 1680 m passed through volcaniclastic sediments almost exclusively. These sediments had the character of marine deposits in medium to abyssal depths, with the basal sediments dating from the Lower Miocene (Tongilava and Kroenke, 1975; Katz, 1976). The change in sedimentation marked by the transition to pelagic and reef limestones occurred at a depth of about 300 m and in time between the Upper and Lower Pliocene (about 3.5 Ma). Elsewhere, multichannel reflection profiling indicates a thickness in excess of 3000 m (Kroenke and Tongilava, 1975; Katz, 1976), although the profiles measured by *R/V Lee* in 1982 showed from 2 to 3 km over the Tonga platform.

Data collected on the Lau and Tonga ridges make it possible to retrace the history of the zone:

1. Eocene—a shallow marine fauna of Upper Eocene age is found on both ridges. The fauna is the oldest in the zone and overlies undated volcanics on

Eua. This volcanic basement is made up of rocks of tholeiitic island arc type.
2. Miocene—the Lower and Middle Miocene are unchanged on the two ridges. According to Gill (1976), the petrographic data imply the two ridges were still contiguous (Fig. 3). In the schema of a single Lau–Tonga arc, Lau would represent the forearc and the volcanic line, while Tonga comprises the area between the forearc and the trench under which the Pacific plate is descending from east to west.
3. Pliocene—the Miocene island arc was disrupted at about the Upper Miocene–Lower Pliocene limit. One consequence of this rupture of the Lau–Tonga ridge was the formation of the Lau basin which developed along a zone of structural weakness such as those followed by lines of volcanos.

After the opening of the Lau basin, volcanism continued along the Lau ridge (2.8 Ma) and until even later in Fiji (Taveuni, 2000 to 700 yr).

The petrographic data of Gill (1976) confirm Karig's (1970) hypothesis in which he regarded the Lau and Tonga ridges as two parts of the same arc presently separated by the opening of the Lau interarc basin. The hypothesis finds further support from morphology and sedimentology. There exists, in fact, a symmetry between the ridges with respect to the Lau basin—a morphological symmetry, for the facing flanks are more abrupt than the external slopes, and a sedimentological symmetry, in the distribution and thickness of the sediments.

3. *The Lau and Havre Basins*

The study of the Tonga–Kermadec arc is incomplete without consideration of the Lau basin and the Havre trough.

Karig (1970) was the first to regard the Lau and Havre basins as interarc basins due to spreading. During the opening of the Lau basin, the tholeiitic basalts emitted were fairly similar to those of midoceanic ridges, but showing an island-arc tendency in their isotopic character and in the presence of certain trace elements (Gill, 1976).

Following Karig, Chase (1971) and Sclater *et al.* (1972) studied the opening of the Lau basin in which the Peggy Ridge played the role, by turns, of axis of spreading or transform fault. However, according to Hawkins (1974), the ancient arc was not split, rather a new one was created by the migration eastwards of the seismic zone.

Weissel (1977) proposed a two-stage opening of the Lau basin, the first between 6–5 and 3.5 Ma was the opening corresponding to the present Havre trough, and from 3.5 Ma to the present day, consequent upon a ridge jump, the present opening forms a triple junction formed by the north–south spreading axis and two transform faults (the Peggy and Roger ridges). It must be noted that, according to

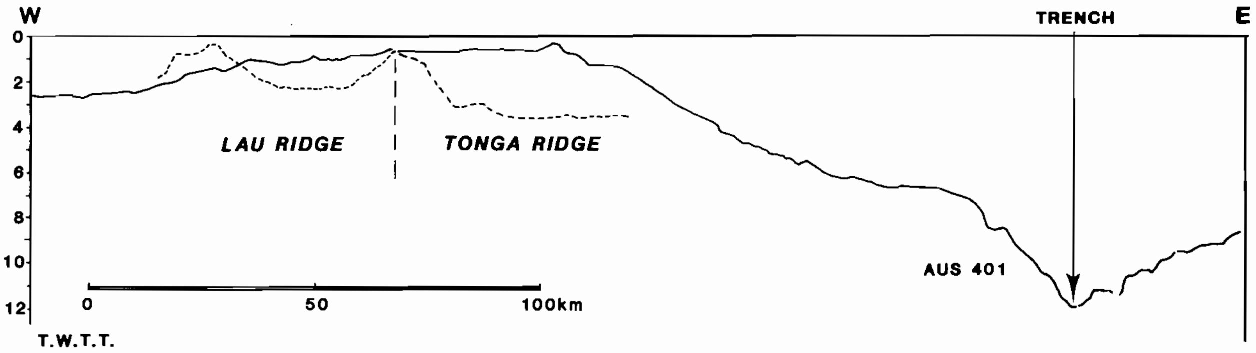

Fig. 3. Hypothetical reconstruction of the Lau–Tonga protoarc from the juxtaposition of bathymetric profiles of the Lau ridge and the Tonga arc (AUS 401). The reconstruction relies only on the morphology of abrupt opposing flanks. The present volcanic line, the Tofua trough, and the eastern flank of the Lau ridge are dashed.

Malahoff *et al.* (1982), the opening of the Lau and Havre basins is more recent—between 2.5 and 1.8 Ma.

II. MORPHOLOGY OF THE TONGA–KERMADEC ISLAND ARC

The existing bathymetric maps (Mammerickx *et al.*, 1971; Eade, 1971; Hawkins, 1974) show morphological differences between the Tonga and Kermadec ridges. More recent work by the *N/O Noroit* and *Coriolis* and by the *R/V Lee* allows a precise definition of the morphological character of the oceanic plate and the arc-trench system. Each of these zones will be studied in turn; certain of the morphological characteristics are summarized in Table I.

A. The Pacific Plate

The oceanic crust generated at the East Pacific Rise forms the Pacific plate which fronts the Tonga–Kermadec arc. The depth of the plate is relatively uniform, between 5100 and 5800 m. Beyond the 5800-m isobath, depth increases rapidly down the outer flank of the trench (Fig. 4).

On the plate, seamounts or isolated guyots provide significant relief, but in the majority of cases, they do not break the surface. There are, from north to south:

- In the north Tonga zone, at 15°S, 172°10′W, a peak rising from the Tonga Trench that reaches to within 1460 m of the surface from a depth of 4400 m
- At 18°30′S and 172°15′W, borders and deforms the Tonga Trench, the Capricorn seamount which rises about 4400 m to a peak 730 m below the surface
- South of the Kermadec, at 35°30′S and 176°W, a seamount whose base is at −5120 m and whose peak is less than 365 m below the surface

In addition to these isolated seamounts, the oceanic plate is cut by a northwest–southeast-oriented ridge which ends in the trench in the Ozbourn guyot (26°S, 175°W). This topographic relief, in part in the trench, delimits the Tonga and

TABLE I
Principal Morphological Parameters of the Tonga and Kermadec Island Arc

Arc	Length of the trench	Maximum depth of the trench	Volcano–trench distance	Art crest–trench distance
Tonga	1.550 km[a]	10.882 m[b]	170–206 km[c]	116–155 km[c]
Kermadec	1.250 km[a]	10.047 m[b]	150–180 km[c]	150–180 km[c]

[a] After Mammerickx *et al.* (1971).
[b] After Faleyev *et al.* (1977).
[c] After Dupont (1982b).

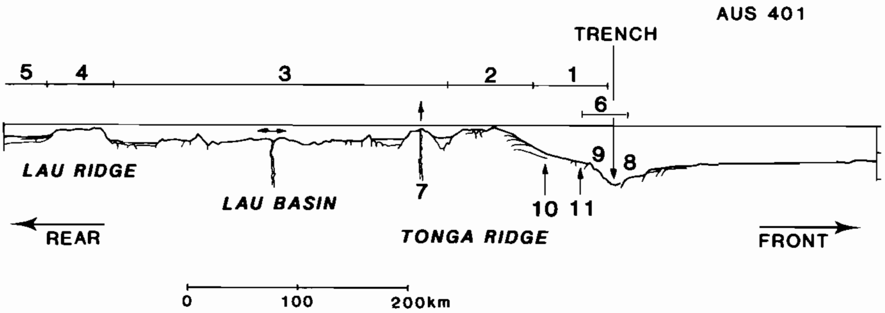

Fig. 4. The principal structures of the island arc (after Karig and Sharman, 1975; Dupont, 1982b) from profile AUS 401. 1, accretionary prism; 2, frontal arc; 3, active marginal basin; 4, remnant arc; 5, inactive marginal basin; 6, subduction zone; 7, volcanic chain; 8, outer wall of the trench; 9, inner wall of the trench; 10, upper slope discontinuity; 11, trench slope break.

Kermadec trenches. The ridge, called the Louisville Ridge, in reality consists of a sequence of isolated eminences still poorly known. Some authors (Hayes and Ewing, 1971) consider it as a possible prolongation of the Eltanin fracture zone, although this is not firmly established.

Although there are no certain data on the age of the oceanic crust bordering the Tonga–Kermadec arc, there is, nevertheless, a general convergence from several lines of research to indicate an age of about 130 Ma:

- The relationship of age as a function of depth (Parsons and Sclater, 1977), giving 120 Ma for depths of 5900 m
- DSDP holes in the Pacific at depths of 5969 and 5981 m, which indicated ages between 130 and 140 Ma without reaching basement (Sclater and Detrick, 1973)
- DSDP hole 204 (Burns *et al.*, 1973) at 5354 m indicated a probable Lower Cretaceous age (130–140 Ma) after penetrating 160 m of oceanic crust

According to Dubois *et al.* (1977), the thickness of the oceanic lithosphere facing the Tonga–Kermadec is between 90 and 110 km.

B. The Tonga–Kermadec Trench

The trench is oriented north-northeast to south-southwest, but at the northern end it bends toward the west and has an east–west trend before attenuating and dying out. To the south, the Kermadec trench, without direction change, becomes progressively less well defined morphologically, and is no longer identifiable at the latitude of North Island, New Zealand.

A longitudinal profile following the axis of the trench (Fig. 5) shows that:

- The deepest part of the Tonga Trench, whose depths exceed 10,800 m, faces the deepest parts of the oceanic plate.

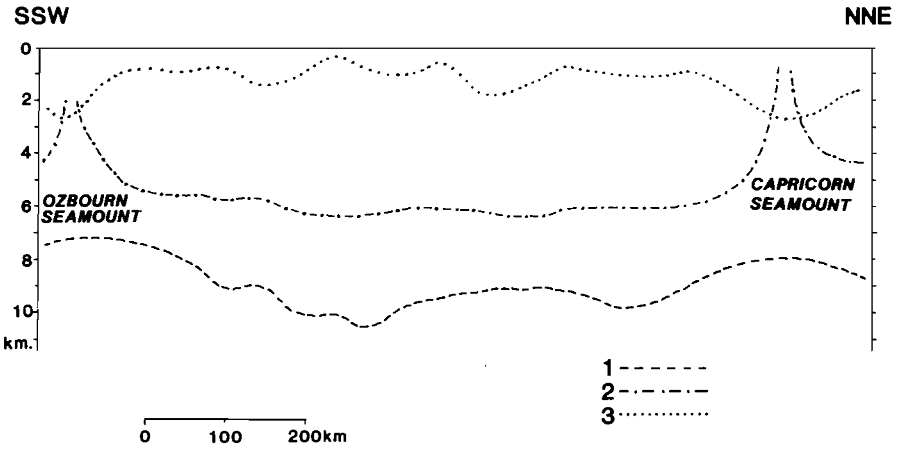

Fig. 5. Longitudinal profiles of the Tonga arc, from the Capricorn seamount to the Ozbourn seamount, based upon 18 bathymetric profiles normal to the arc. The regularity of the downgoing plate between the points of relief (seamounts), and the deepening of the accretionary prism facing the same relief, should be noted. 1, longitudinal section along the axis of the trench; 2, section through the downgoing plate parallel to the trench and intersecting the Capricorn and Ozbourn seamounts; 3, section through the accretionary prism, parallel to the trench.

- The sills in the trench, corresponding to the Capricorn and Ozbourn guyots, still lie on the descending oceanic plate as the guyots gradually descend into the trench.

However, if this morphological comparison is extended to the ridge, then it must be recorded that the seamounts face the deepest parts of the island arc (Fig. 5). According to Dupont (1982b), the relief on a plate plunging toward the base of the trench has an influence on the morphology of that part of the island arc facing it.

The bathymetric profiles and reflection profiles indicate fracturing of the descending plate, which facilitates the adjustment of its curvature and final disappearance under the trench. The network of the present profiles is too wide to determine whether the fractures remain parallel to the trench. Nor, in general, can the reflection profiles show the thin sediment cover over each fractured segment (0.2 to 0.4 sec two-way travel time) (Fig. 6).

C. The Tonga–Kermadec Frontal Arc

Morphologically, the frontal arc is the most elevated part of the island arc. It is crowned by either volcanic or coral islands. In the case of Tonga, it forms a more or less flattened swell 90 to 120 km wide. It lies at variable depths, for it is composed of highs or plateaus with an average depth of 500 m, from which rise the coral islands, separated by deeper water zones which may reach a depth of 1000 m. The arc remains linear and, toward 15°S, abuts the trench. A series of massifs, more or

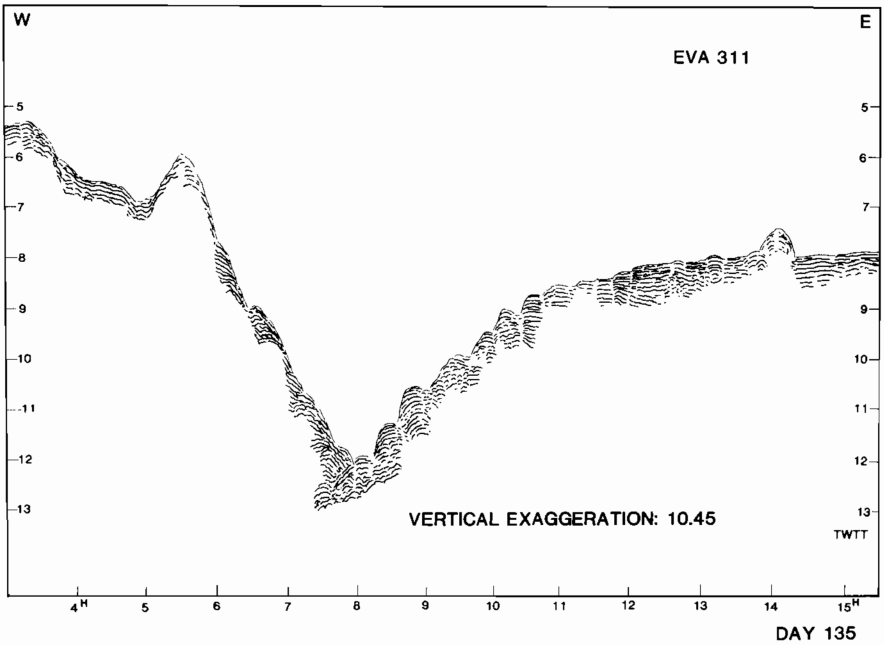

Fig. 6. The fracturing of the Pacific plate due to its curvature prior to descent under the Tonga arc (Australo-Indian plate) (profile EVA 311). Fractures can be distinguished cutting the plate into blocks. In general, the sedimentary cover is too thin and so does not show on the single-channel reflection seismic traces.

less well individualized, mark its continuation to the west along the line of the trench.

The frontal arc can be subdivided into the following three important blocks, delimited by a grid of west-southwest to east-northeast and north-northwest to south-southeast faults (Dupont and Herzer, 1985):

- To the south, a submerged block with an average depth of 500 to 1000 m
- In the center, the most important block, with an average depth of 500 m, on which lie all the coral islands
- A more broken-up northern zone, over which the depth varies from 1000 to 1500 m

There are two discontinuities in the last zone. The first discontinuity, occurring toward 18°30′S, displaces the northern part some 35 km west with respect to the part farther to the south. The distance between the axis of the frontal arc and the trench is 170 km to the north of Vava'u, but is only 140 km to the south. This displacement occurs at about the latitude of the Capricorn seamount. The second displacement, found at about 17°S, seems to be correlated with northwest–southeast structures in the Lau basin, along which is found the Niua Fo'ou volcano (Fig. 7).

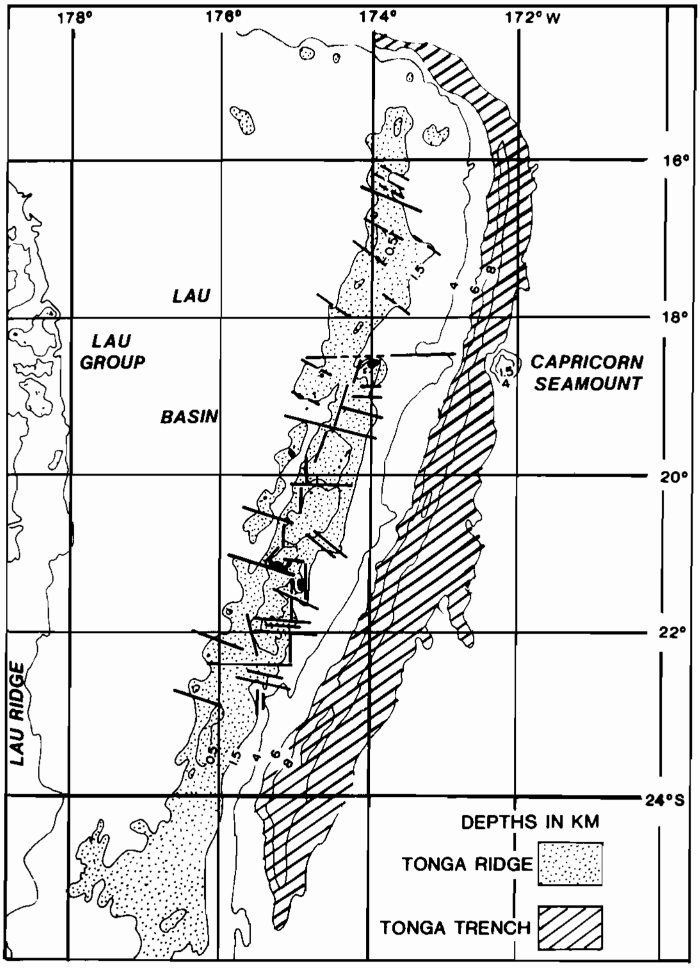

Fig. 7. Network of fractures which cut the Tonga arc into blocks of different size. There is a first system oriented E–W to WSW–ENE approximately normal to the trench, and a second system N–S to NNW–SSE which cuts the first set from the blocks as mentioned (see Dupont and Herzer, 1985). There is, in addition, a third SE–NW fault set. This latter trend is most evident where it cuts the volcanic line, in particular in north Tonga where these faults are responsible for the successive westerly displacements of the crest of the arc.

The frontal arc of the Kermadec has the form of a continuous ridge, the crest of which is, at the same time, the crest of the island arc and the line of the volcanic arc, emergent at several points. The depth between the islands and reefs is highly variable, but there are no large plateaus.

In the Tonga as well as the Kermadec arc, the arc itself is formed of volcaniclastic sediments, as shown by borings on Tongatapu. Volcanic intrusions pierce the sediment layers, which may be broken up by faulting into tilted blocks (Tonga).

From the available data, the thickness of the volcaniclastic sediments may vary from 2000–3000 m (Dupont, 1982b) to 4000–5000 m (Kroenke and Tongilava, 1975; Katz, 1976) in the Tonga arc. In the Kermadec arc, the sediments accumulated between the crest of the arc and the trench slope break, with a thickness which may reach to between 2500 and 4000 m, for sound wave velocities between 2 and 3 km/sec (Dupont, 1982b).

D. The Tonga Volcanic Line and Tofua Trough

In the Kermadec arc, as has been seen, the present volcanic alignment coincides with the crest of the frontal arc, whereas in the Tonga the line of active volcanoes lies behind the frontal arc. The existence of the volcanic line is shown by the following phenomena:

- A series of islands where volcanic activity is marked by fumarolic activity when the volcano itself is dormant
- A series of reefs, relicts of eroded former volcanoes
- A series of submarine volcanoes

The volcanic line is made up of several segments displaced, one from another, by faults (Ewart and Bryan, 1973) as illustrated in Fig. 7. From south to north, each segment is displaced slightly to the west with respect to the preceding segment. Farther to the north, beyond 18°30′S, the volcanic line continues to be displaced westwards, consistent with the westerly displacement of the arc already mentioned; but this is of lesser importance because, between 18°30′S and 15°S, the volcanic line tends to coincide more and more with the crest of the island arc.

The position of the present line of Tonga volcanoes shows that it was displaced by successive jumps. The volcanic basement of Eua and transverse magnetic profiles north and south of the island (magnetic anomaly of 480 gamma) locate the pre-Eocene position of the line. Kroenke and Tongilava (1975) proposed a second alignment parallel to this and to the present alignment, through Tongatapu, Nomuka, and Ha'apai, assigning it a Mio-Pliocene age. Actually, the third alignment is morphologically to the rear of the arc, at least between 23 and 18°30′S, and refraction data even seem to indicate that the volcanoes rest on the crust of the Lau basin or at least at the junction between the Lau basin and the Tonga arc (Figs. 7 and 12).

Refraction lines show that the Tofua trough occurs at the crustal boundary between the Lau basin and the Tonga arc in a tectonically weak zone. The depression, 300 km long and 25–30 km wide, runs parallel to the arc, with a morphology which has been accentuated by movement along faults lying along the western flank margin of the frontal arc. Sediments emitted by the volcanoes along the western margin of the depression are therefore trapped within the depression and have accumulated to a considerable thickness (2500 m) (see Figs. 8 and 12).

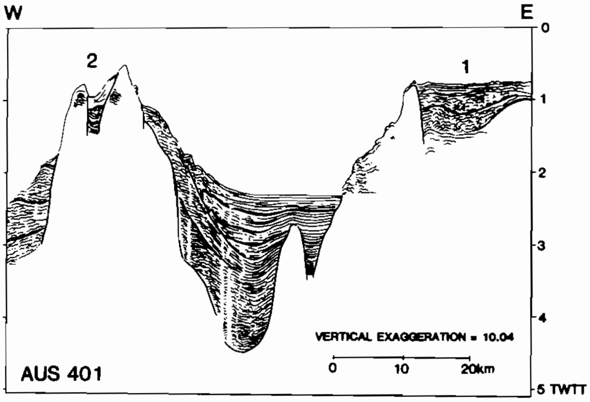

Fig. 8. Transverse section of the Tofua trough (reflection profile AUS 401). 1, Crest of the arc north of the Ha'apai island group; 2, submarine volcano. (After Dupont, 1982b.)

E. Morphological Evolution of the Tonga and Kermadec Arcs

Following the classification of island arcs based upon morphological characteristics (Karig and Sharman, 1975), Dupont (1979, 1982b) defined the morphology of the Tonga–Kermadec arc from a study of more than 30 transverse profiles. He classified the profiles into three families (Fig. 9) which are, in their order of evolution:

- Kermadec, or original morphology stage
- Ozbourn–Capricorn, or transitional morphology
- Tonga, or the morphology of the final stage

In a geographical sense, these morphological types can be ordered from south to north as follows (see Fig. 10):

- Kermadec arc, original stage
- Area of Ozbourn seamount, transitional stage
- Southern part of the Tonga arc, final stage
- Area of Capricorn seamount, transitional stage
- Northern part of the Tonga arc (18–15°S), original stage

According to Dupont (1979, 1982b), subduction of the Louisville ridge is the principal cause of the morphological changes recorded in the arc, but the geographical distribution of the three families of profiles poses a problem. Although the morphology of the Kermadec, Ozbourn, and southern part of Tonga may easily be explained by the subduction of the Louisville ridge beneath the Tonga–Kermadec arc as a consequence of Pacific plate motion, the northern part, in contrast, is not involved. Only by using the seismic data from the North Tonga region (Louat and

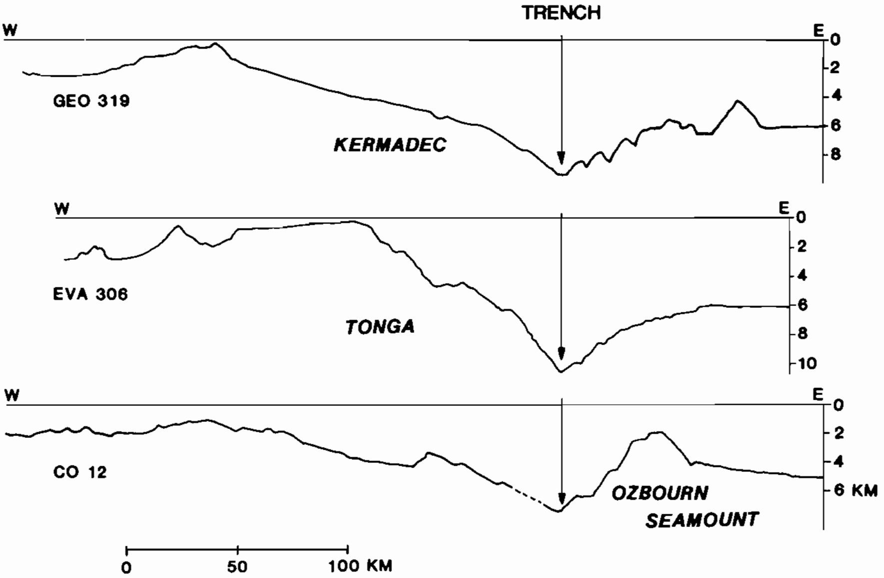

Fig. 9. Three profiles which characterize the morphology of the Kermadec (GEO 319), Tonga (EVA 306), and the zone opposite the Capricorn or Ozbourn seamounts (CO 12). The profiles are typical of the three morphological families defined by Dupont (1982b) and illustrate that author's hypothesis on the morphological evolution of the Kermadec and Tonga.

Dupont, 1982), which show that the Benioff zone is shallower in the north than in the south, can an explanation be found for the morphology of the northern zone. The entire North Tonga region is of recent formation (3–4 Ma) and, hence, its morphology has in no way been affected by the subduction of the ridge. Only the occurrence of the Capricorn seamount locally modifies the morphology of the arc.

If the effect of a subducted ridge on an island arc is to be admitted, then it must be established that the morphology of all arcs depends upon:

- The type of topographic relief existing or having existed on the subducted plate
- The orientation of the relief on the plate
- The direction of motion of the plate with respect to the subduction zone

The effect of isolated topographic relief, such as the Capricorn guyot, can only have a local influence on arc morphology, in contrast to the effect of a ridge such as the Louisville Ridge. Yet, a ridge perpendicular to an arc and trench, and moving approximately perpendicular to them, would have the same effect as an isolated seamount. The effects on the morphology of the arc are most apparent in the frontal arc and the elevation of this zone, and not only explain the numerous evidences of vertical uplift in this part of the island arc, but more particularly the uplift of the

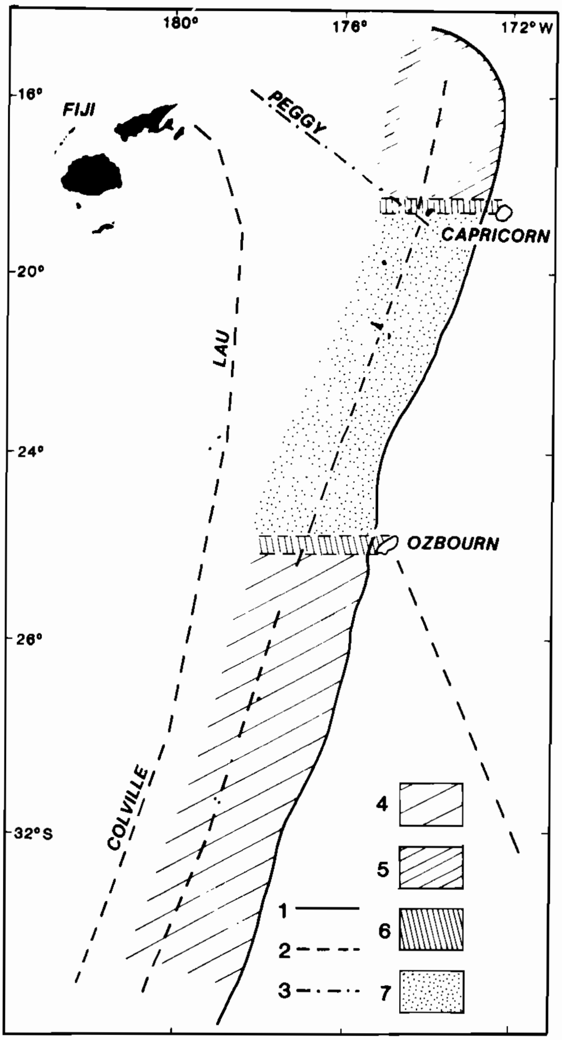

Fig. 10. Geographic distribution of the three morphological families. 1, Tonga and Kermadec trench; 2, axes of structures; 3, limit of the fossil plate which passes into the Peggy ridge; 4, location of the Kermadec morphological family; 5, same morphological type as the preceding, but reflecting recent subduction in north Tonga; 6, Ozbourn and Capricorn morphological family; 7, Tonga morphological family.

great thickness of sediments which accumulated in the deep waters over the flank of the arc between the crest and slope break.

At the present time, the motion of the Louisville ridge on the Pacific plate is toward the Kermadec. If the Louisville Ridge were a continuous chain instead of being a series of isolated prominences (Hayes and Ewing, 1971; Mammerickx *et al.*, 1971), vertical uplift ought to have been found of the frontal arc south of Tonga, and a trench either absent or much shallower than normal, as is the case in the New Hebrides opposite the d'Entrecasteaux ridge (Daniel *et al.*, 1982; Jouannic *et al.*, 1982).

III. DEEP STRUCTURE OF THE TONGA AND KERMADEC RIDGES

A. Refraction and Gravimetric Study of the Arc

1. *Data Acquisition*

While methods for investigating deep structure such as seismic refraction and gravimetry provide evidence of the internal structure of the Tonga–Kermadec arc, their results are too sparse for an arc of such importance. They also tend to be localized, particularly in Tonga, which gives an inadequate view of the structure as a whole.

The first refraction data were acquired by Raitt *et al.* (1955) and were augmented by the ORSTOM EVA cruises (Pontoise and Latham, 1982). These first refraction lines penetrated layer 3 and into the upper mantle below the Mohorovicic discontinuity, and were amplified by a second series that was carried out by petroleum companies and by the *R/V Lee* using refraction buoys. The latter, however, rarely provided more than seismic velocities in the upper layers of sediment.

Gravimetric data are not plentiful. In their discussion of a transverse gravimetric profile, Talwani *et al.* (1961) incorporated Raitt's refraction data. In 1971, NOAA recorded four long profiles in the Tonga arc, of which 2D had the advantage of not only being very long but also almost perpendicular to the structure of the arc (Lucas, 1972). Gravimetric profiles were also recorded by the *R/V Vitiaz* (Kogan, 1976). The more recent data consist of a profile perpendicular to the arc and trench and parallel to a refraction profile carried out by ORSTOM. Starting at 20°S, 169°5′W, the profile traverses the downgoing plate, trench, and island arc, and ends at the margin of the Lau basin at 19°5′S, 175°5′W (Missègue and Malahoff, 1982). It was completed by the seismic refraction work of Pontoise and Latham (1982) who used a Bolt airgun with a 15-liter chamber as a source and an ocean bottom seismograph as a recorder, following the method of Lathan *et al.* (1978).

2. *Structure of the Ridge*

The refraction and gravimetric data are recorded in Fig. 11, and the principal features are discussed passing from east to west.

(a) The Downgoing Plate. This is formed of three layers which can be described in the following manner:

- A thin sedimentary layer which cannot be recognized in refraction profiles, but which is clearly visible in reflection profiles. The relative thinness, less than 400 m, is essentially due to the distance from terrestrial or volcanic sources and the depth of deposition, which is always greater than the carbon-

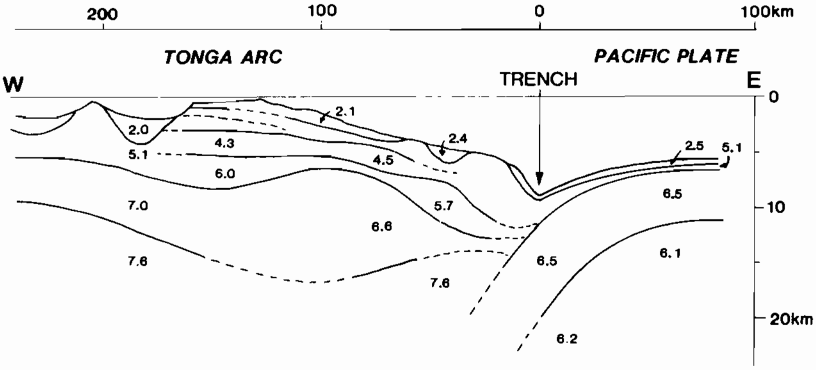

Fig. 11. Sketch of the deep structure of the Tonga arc, based on seismic refraction (Pontoise and Latham, 1982), amplified by gravimetric data (Missègue and Malahoff, 1982), with respect to the ascent of dense material to 14.5 km along the outer surface of the subducted lithosphere.

ate compensation depth. The gravimetric data provide evidence of a thin sedimentary layer with a density of 1.97, which agrees remarkably well with the first horizons visible in the reflection profile.

- Layer 2 is also thin (about 600 m) with a velocity of 5.3 km/sec. It thickens toward the trench, which may be the result of the onset of accretion. The gravimetric model of Missègue and Malahoff (1982) gives a density of 2.55 for the layer corresponding to layer 2, but this layer seems already to thicken 30 km east of the trench. The gravimetric as well as the refraction data show that the zone of accumulation, classically situated at the contact of the plates, may begin well before reaching the trench by the thickening of layer 2.
- Layer 3 has a thickness of 4.5 km and a velocity of 6.5 km/sec. The thickness is abnormal for layer 3 of an oceanic plate. At the trench, it dips under the arc at an angle of 56°. The best-fit gravimetric model requires a density of 2.81 and a thickness of 5 km—that is, be even thicker than indicated by refraction and dip at no more than 50°, which approximates to the angle indicated by refraction.

The velocities of 8.1 and 8.2 km/sec seen on the refraction profiles of Raitt *et al.* (1955) are characteristic of upper mantle velocities immediately below the Mohorovicic discontinuity. In the trench, the discontinuity plunges to a depth which varies according to the method used—to about 20 km from refraction, but only 17.5 km by gravimetric calculation.

Finally, the characteristic bulge of the oceanic lithosphere before dipping under the arc is particularly clearly seen on NOAA long profile 2D. The maximum upwarping lies 220 km east of the Tonga trench (Lucas, 1972).

(b) The Contact Zone of the Plates/Accretionary Prism:

- The first observation to make is of the failure of seismic reflection, and gravimetry even more so, to indicate the presence of accumulated sediment at the bottom of the trench. Thus, if there are sediments, they are most assuredly very thin. Hence, there is no accumulation in the trench but a disappearance or accretion of the sediments of the downgoing plate under or onto the island arc.
- Layer 2 can be broken down into layers 2a, with a velocity of 4 km/sec, and 2b, with a velocity of 6 km/sec.
- Layer 3 can be similarly divided into layer 3a, which has a velocity of 6.9 km/sec, and 3b, 7.6 km/sec. Layer 3b should be at a depth less than 15 km.

The gravimetric data for the upper layers are no better than the refraction data, but they do confirm that, at the point of contact of the plates under the accretionary prism, the Mohorovicic discontinuity is at a depth of 14.5 km. However, the upper mantle velocities below the Tonga arc are not above 8 km/sec as under the downgoing slab, but are only on the order of 7.6 km/sec.

(c) The Island Arc. The refraction profiles detail the arc structure and, in particular, point to a marked thickening of layers 2 and 3. In these lower layers, the velocities recorded are always below the velocities normally measured in the upper mantle—7.6 km/sec instead of 8.1 or 8.2 km/sec.

If velocities of 7.6 km/sec can be accepted as characteristic of the type of upper mantle found below island arcs, then the thickness of the crust below the Tonga arc is about 16 km. The incompleteness of the gravimetric data for this segment of the arc permitted Missègue and Malahoff (1982) to only estimate a possible Mohorovicic depth of about 35 km, a figure which does not agree with that calculated from the refraction results.

(d) The Backarc Zone. In the backarc area, i.e., the zone of the Tofua trough and the volcanic line, the refraction data bring out the different characteristics of the sediments in the Tofua trough and those of the arc *sensu stricto.* A great thickness of unconsolidated sediments (see Fig. 8), thus of relatively recent age, is found in the trough, whereas on the arc, below a thin layer of recent unconsolidated sediments, there are thicker layers with velocities in the range 2.7 to 3.5 km/sec which are formed by older sediments in the process of consolidation.

The variety of the layers, as much in seismic velocity as in thickness, seems to delimit two distinct zones of different age and origin. The Tofua trough thus lies at the junction of these two zones, as is underlined by Fig. 12. As for the crust of the Lau basin, it has all the characteristics of young oceanic crust, and the great thickness of unconsolidated sediments shown in Fig. 11 finds an explanation in its proximity to the volcanic line.

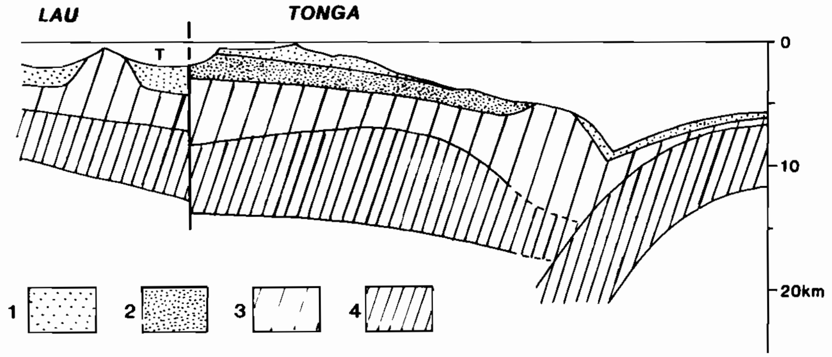

Fig. 12. Schematic representation of the structure of the Tonga arc, illustrating the differences between the crust of the Lau basin and that of the island arc. The boundary between the two corresponds to the break of the protoarc Lau–Tonga. T, Tofua; 1, 2.0–2.5 km/sec layer; 2, 2.7–3.5 km/sec layer; 3, layer with 3.8–6.0 km/sec velocity; 4, layer with 6.4–7.2 km/sec velocity. Under layer 4, velocities range from 7.6 to 7.7 km/sec under both the Lau basin and the Tonga arc. Under the downgoing slab, velocities are on the order of 8.2 km/sec. (After Dupont *et al.*, 1982.)

3. *Conclusions*

Gravimetric data show that the Mohorovicic discontinuity rises below the accretionary prism, with dense material (d = 3.33) rising to 14.5 km. The modeling of Missègue and Malahoff (1982) demonstrates that it is necessary to take this fact into account if the theoretical curve of the calculated anomaly is to most closely approximate the observed curve. This rise of dense material along the side external to the downgoing plate was interpreted by Elsasser (1971) in terms of a shear at the plate contact resulting from the convergence of the plates and the density of the downgoing slab, a shear which facilitated the rise of denser material. This phenomenon, too little studied, has still to be verified and proved.

Below the Tonga arc, a crustal thickness of less than 16 km is recorded in which seismic velocities do not exceed 7.6–7.7 km/sec, while Shor *et al.* (1971) found velocities in the upper mantle of 8.1 km/sec below a crustal thickness of 18.4 km in the Kermadec arc. The velocity of 7.6 km/sec in the upper mantle below the Tonga arc approaches that found under the New Hebrides arc, where velocities of 7.7 to 7.9 km/sec were recorded by Pontoise *et al.* (1980, 1982) and Daniel *et al.* (1982).

As Table II indicates, comparisons of the three island arcs in the southwest Pacific are difficult insofar as age, crustal thickness, and upper mantle velocities are concerned.

Should the current data be doubted or should they be regarded as indicating that the island arcs may have, for reasons as yet unknown, a crust of variable

TABLE II
Comparison of the Crust under Three Island Arcs as a Function of Age[a]

Arc	Crustal thickness	Upper mantle velocity	Age of the island arc
Tonga	16 km	7.6–7.7 km/sec	45 Ma
Kermadec	18 km	8.1 km/sec	45 Ma
New Hebrides	26 km	7.9 km/sec	10 Ma

[a] After Daniel *et al.* (1982).

thickness over an upper mantle in which velocities range from 7.6 to 8.1 km/sec? All this goes to underline the need to augment refraction and gravimetric data from the Tonga–Kermadec ridge.

B. Seismological Study of the Subduction of the Pacific Plate below the Tonga–Kermadec Arc

1. *Introduction*

The existence of subduction in the Tonga–Kermadec region was demonstrated by Oliver and Isacks (1967) and Isacks *et al.* (1968, 1969) in their interpretation of seismological data. The seismic foci they found defined a continuous narrow zone which extended from zero to 700 km in depth. In this zone, seismic waves were little attenuated and had high velocities, whereas in the enclosing asthenosphere, particularly in the backarc region, only the low-frequency waves were recorded at local seismological stations. The focal mechanisms of shallow earthquakes were thrust displacements in the majority of cases, leading the authors to claim the descent of the Pacific plate below the Tonga–Kermadec arc—thereby adding the phenomenon of subduction in the context of plate tectonics.

In addition to the descent of the Pacific plate below the Australo-Indian plate, seismology also shows the transition of this subduction zone to a sinistral east–west transform fault north of Tonga (Isacks *et al.*, 1968, 1969) and the continuity of the Benioff zone between Tonga and Kermadec (Isacks and Barazangi, 1977).

The geographic distribution of seismicity is not uniform; there is a minimum of activity at the junction of the Tonga–Kermadec trench and the Louisville ridge, and to the north, a zone of strong activity marking the passage of the subduction into an east–west transform fault (Louat, 1977).

Finally, west of the Tonga and Kermadec ridges there are found the Lau and Havre basins, respectively. The upper mantle below the Lau basin is characterized by a marked attenuation of P and S wave velocities, with the eastern boundary of this zone lying near the active volcanic line of Tonga (Fig. 13). These characteristics do not seem to extend to the Havre trough (Barazangi and Isacks, 1971; Aggarwal *et al.*, 1972).

The morphology of the Benioff zone varies according to author. According to Isacks and Barazangi (1977), it can be represented by three sections drawn through Kermadec, northern and southern Tonga (Fig. 14). Despite the difference in the dip of the Benioff zone between south Tonga and Kermadec, the authors demonstrate the continuity of the Benioff zone between Tonga and Kermadec. Hanuš and Vaněk (1979) grouped their seismic data along lines perpendicular to the trench. From the distribution of earthquakes, they argued for the existence of an earlier subduction zone preceding the present Tonga–Kermadec subduction (Fig. 15). To these two phases of subduction separated in time, there may be added two further fossil subduction zones—the so-called Lau zone lying west of the present Tonga–Kermadec trench, and the Horn (or Futuna Island) zone north of Tonga. Hanuš and Vaněk (1979) further concluded that the rate of subduction of the Pacific plate is variable and that, in particular, the subduction of relief, a chain, or seamount (Louisville ridge or Capricorn seamount) may slow down the rate of disappearance of the downgoing plate.

A study by Louat and Dupont (1982) was based upon a similar principle. In interpreting the thickness of the seismic zone and its dip, it is usual to consider sections normal to the trench on which foci are positioned as a function of depth, the technique used by Hanuš and Vaněk whose method on deep earthquakes (400 to 700 km) in the Tonga–Kermadec area led them to conclude that the direction of subduction has not varied since its inception 45–50 Ma according to geological estimates. Louat and Dupont (1982) concluded, from a study of an east–west section, that it was possible to discern a coherent pattern in the deep Benioff zone between 35 and 22°S (sections A–D, Fig. 16). Farther north, between 22 and 18°S, the interpreta-

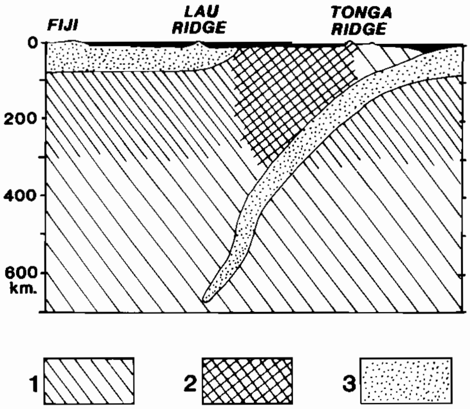

Fig. 13. Schematic section across the Tonga arc, Lau basin, and Lau ridge, showing the zones of low, extremely low, and high attenuation. 1, low attenuation; 2, extremely low attenuation; 3, high attenuation. (After Barazangi and Isacks, 1971.)

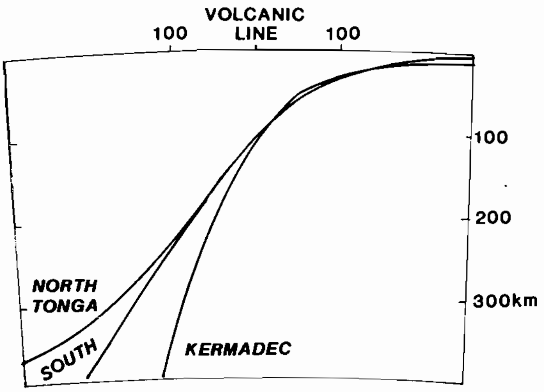

Fig. 14. The morphology of the Benioff zone of Tonga and Kermadec, according to Isacks and Barazangi (1977), showing the high dip of the Benioff zone in the Kermadec and its decrease in the South Tonga and North Tonga.

tion of the sections (E–H in Fig. 16) is only possible by adopting the pattern seen farther to the south. The paucity of seismic stations, due to the distribution of the islands, can induce considerable uncertainty in the localization of earthquakes recorded by only a small number of stations, and for this reason, Louat and Dupont (1982) selected only the better established events, retaining only those earthquakes recorded at more than 100 stations.

From the study of earthquakes from successive depths—deep, intermediate, and shallow—different hypotheses have been formulated, as below.

2. *Deep Earthquakes*

Since about 30 Ma (Packham and Andrews, 1975), the rotation pole between the Pacific and Australo-Indian plates, assuming the latter fixed, has lain south of

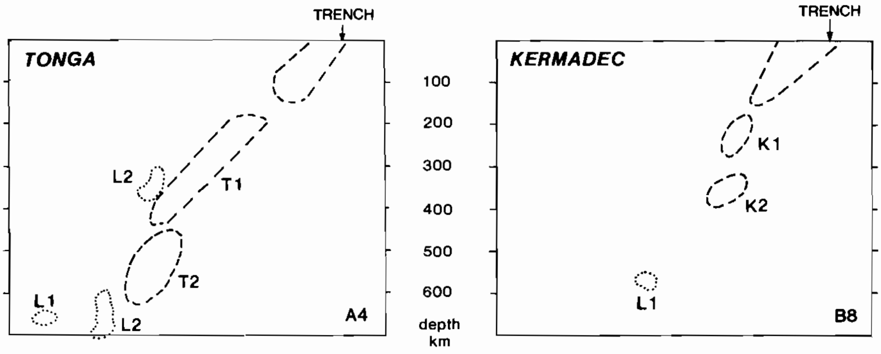

Fig. 15. The morphology of the Benioff zone of Tonga and Kermadec, according to Hanuš and Vaněk (1979). On the section through Tonga (A4 near 20°S), the interpretation of the different subductions is shown: L2 and L1, fossil subduction of Lau; T2, former subduction of Tonga; T1, present subduction. On the Kermadec section (B8, about 30°S): L1, fossil subduction of Lau; K2, former subduction of Kermadec; K1, present-day subduction.

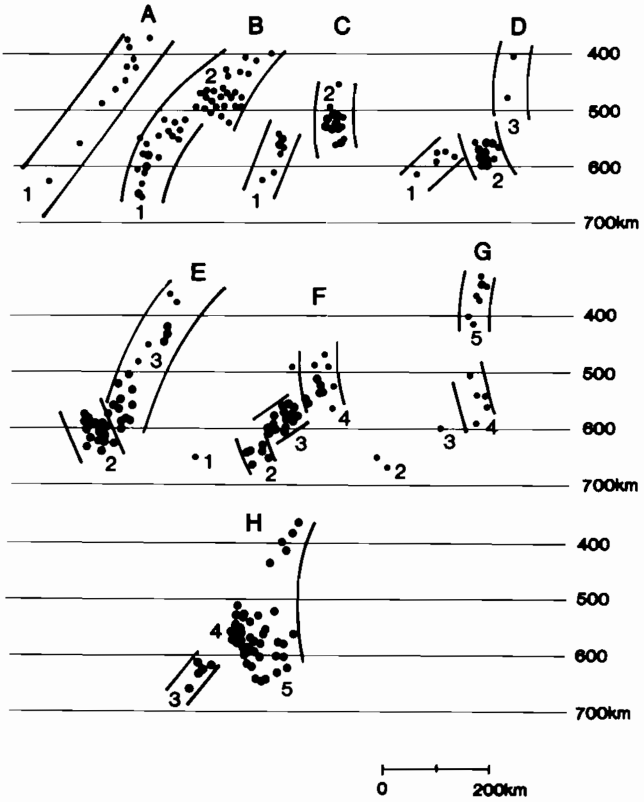

Fig. 16. The interpretation of seismic sections of Tonga and Kermadec, based on deep earthquakes (400–700 km), according to Louat and Dupont (1982). Section A groups earthquakes between 33 and 28°S; B, between 27 and 24°S; C, between 24 and 23°S; D, between 23 and 22°S; E, between 22 and 21°S; F, between 21 and 20°S; G, between 20 and 19°S; H, between 19 and 18°S. The numbers 1 to 5 represent the different segments of lithosphere subducted after rupture.

the Kermadec, with the present pole lying at approximately 60°S, 180°. Consequently, the velocity of convergence of the plates is lower in the Kermadec than it is in Tonga, and it is therefore to be expected that the subducted plate is shorter and thus, *a priori,* simpler. Figure 16 shows a Benioff zone becoming more complex from south to north.

Louat and Dupont (1982) suggested that the maximum depth of the Benioff zone is 700 km and, having attained that depth, it cannot descend farther. This depth, therefore, occupies the role of a buffer zone or anchor point. The Benioff zone begins to flex at depths between 400 and 500 km (section B, Fig. 16); then, as subduction continues, a break develops in the subducted slab at about 500 km, and the slab continues to descend behind the break (the beginning of rupture is shown in section B and subsequent stages in C and D). When the newly fractured edge itself reaches 700 km, there is a new flexure and rupture and continued descent of the plate; this is shown schematically in Fig. 17. The blocking of subduction at 700 km at first modifies the geometry of the Benioff zone by creating a flexure; then, in succeeding stages, it constrains the plate margin—i.e., the trench, causing it to migrate eastwards. Following this, the rupture and renewed subduction of the Benioff zone are due either to a gravity effect operating on the subducted plate or to a change in the direction of subduction.

The successive changes in the direction of subduction may be deduced from the changed orientation of deep earthquakes. The distribution of these earthquakes may be illustrated by several sections of curves which are unrelated to the trends of the present Kermadec, Tonga, and North Tonga trenches, but which indicate the evolution of prior subduction in the region (Fig. 18).

At the latitude of the Fiji Islands, the deep earthquake foci are oriented southeast–northwest and can be interpreted as the result of two phenomena: (1) an ancient subduction which marks out the Fiji platform and which may be linked to the Vitiaz trench and to the deep earthquakes of the North Fiji Basin; (2) the subduction of the Louisville ridge which is prevented from extending deeper than 600 km by the buoyant material of which it is formed.

3. *Intermediate Earthquakes*

The work of Louat and Dupont (1982) on the intermediate earthquakes, although indicating a change in the dip of the Benioff zone (see Fig. 14), in no way changes the regularity and continuity of the zone—conclusions earlier underlined by Isacks and Barazangi (1977). However, the former authors considered that the change in dip was not solely a consequence of the subduction of the Louisville ridge, but that it was much more a response to the arresting of subduction at 700 km which leads to a flexing of the subducted lithosphere when movement continues.

(a) The Kermadec. The intermediate focus earthquakes in the Kermadec, as the deep earthquakes, show that the Benioff zone in this region has not been altered by the movement of plate boundaries or by changes in the orientation of the con-

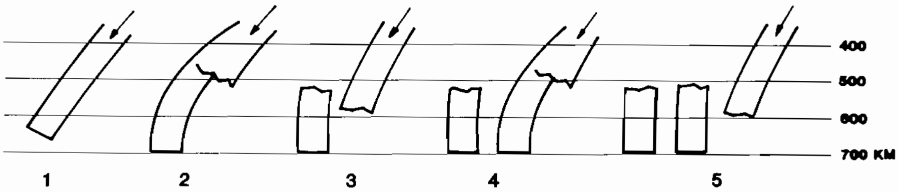

Fig. 17. Schematic interpretation of the mechanism represented in Fig. 16. 1, dip of downgoing lithosphere to 700 km; 2, flexing and rupture after motion is arrested at 700 km; 3, dip behind the first slab of the newly fractured slab; 4 and 5, continuation of the mechanism. The arrows indicate the direction of motion of the subducted lithosphere.

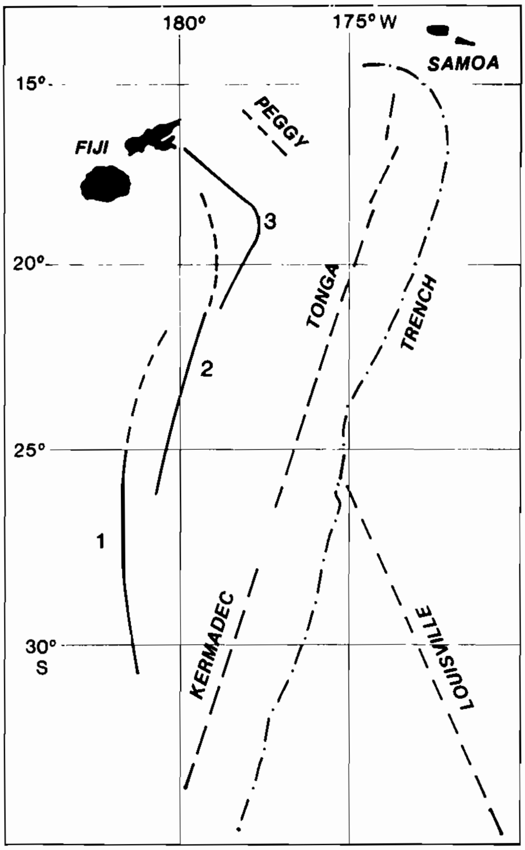

Fig. 18. Distribution of deep earthquakes of the Kermadec–Tonga showing the change in orientation and illustrating the migration of the Benioff zone. 1, original direction, little different from present subduction. 2, first direction change; the change in the south is very little different from the present zone but, in contrast, the northern part shows an inflection of the subduction zone around the Fiji platform. 3, orientation of subduction prior to the formation of the north Tonga zone. (After Louat and Dupont, 1982.)

verging Pacific and Australo-Indian plates. The northern part of the Benioff zone in the Kermadec area may still represent original subduction.

In the southern part of the Kermadec, the surface trace of the intermediate earthquakes curves westwards, and this seismicity ceases abruptly between 32 and 33°S. These features may be linked to the existence of an ancient major fault trending southeast–northwest through this area, and can be correlated with changes in the morphology of the Havre trough and the hypothetical Cook fracture zone (Mammerickx *et al.*, 1971).

(b) The North Tonga. In the north Tonga region, the principal seismic discontinuity in the intermediate earthquakes is not correlated with the trace of the trench between the Tonga and Samoa archipelagos, and the same is true of shallow earthquakes, especially in the Lau basin where they have a southeast–northwest trend (Fig. 19). This distribution of intermediate and shallow earthquakes was interpreted by Louat and Dupont (1982) as indicating the existence of an old boundary between the Pacific and Australo-Indian plates. This boundary was formerly situated along a

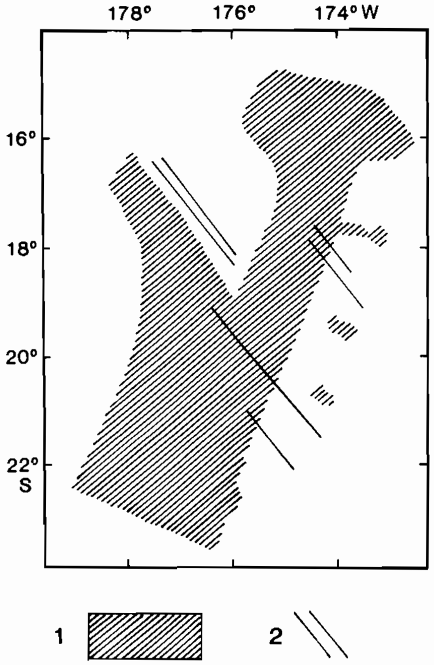

Fig. 19. Shallow and intermediate seismicity of the north Tonga region. Intermediate earthquakes (100–500 km) in hachures (1) show a seismicity gap and a turn to the northwest of the subducted zone and the shallower part of the subduction zone in the extreme north. Only in the Lau basin does the shallow seismicity (2) retain a SE–NW orientation. (After Louat and Dupont, 1982.)

northwest–southeast line at 50°W, beginning from a region close to the Vava'u archipelago and coinciding with the Peggy ridge; they did not specify whether it marked a fracture or a subduction zone, in contrast to Hanuš and Vaněk (1979) who considered it to be a fracture zone.

Present-day subduction between 19 and 15°S may be understood in terms of a northward migration of Tonga–Kermadec subduction, a phenomenon possessing, in its own right, extensional dynamics which lead to the conclusion that the Lau basin is formed of recent crust. The same phenomenon is also visible in the southern New Hebrides subduction where the same depth of intermediate earthquakes can be observed as in north Tonga and where the Benioff zone is quite as irregular as that of north Tonga. It thus seems that the extremities of subduction zones may display similar characteristics, whatever the region. The north Tonga region shows that the Tonga–Kermadec subduction has produced secondary movements, prolonging subduction to the north. The region is still evolving.

Nevertheless, it has to be reported that the study of the extreme northern Tonga by Louat and Dupont is based on the convergence of the trace of intermediate and shallow focus earthquakes recorded at less than 100 stations, and on the morphology of the arc. If an epicenter whose location is in no doubt can be found lying within the zone, which these authors consider as a permanent gap in intermediate seismicity, all their conclusions will require revision. However, using a similar method with some variations, Hanuš and Vaněk arrived at similar conclusions, in particular on the existence of an ancient boundary between the plates along the Peggy ridge.

4. *Shallow Earthquakes*

Shallow focus earthquakes in the Tonga–Kermadec island arc have been associated with subduction, principally through the interpretation of focal mechanisms. Johnson and Molnar (1972) distinguish three kinds of mechanism: thrust mechanisms (subduction), tear (hinge) faulting mechanisms, and mechanisms resulting from internal tension due to the flexuring of the descending Pacific plate.

Along the length of the Tonga–Kermadec arc, earthquakes which can be tied to tension at plate contacts can be grouped in a zone about 40 km wide at Tonga and 70 km in the Kermadec. The transition between the two zones is marked by a seismicity gap toward 26°S, opposite the Ozbourn guyot (Louisville ridge). It should also be noted that there are concentrations of shallow earthquakes in front of the arc where the trench is deformed, where the trench bends in north Tonga and north and south of the contact of the Louisville ridge and the island arc.

The shallow earthquakes north of Tonga interpreted by Isacks *et al.* (1969) as the east–west shearing of the Pacific plate form a group of earthquakes oriented about 30°W. The shear is marked by a network of shallow and intermediate faults spread over 100 km from the curvature of the trench. Farther to the west, the margin of the plates, which has always been considered as a fracture zone, is not, seismologically speaking, at all well marked by shallow earthquakes.

The reduction of shallow seismic activity toward 26°S seems to have been constant since 1900 (Meyers and Von Hake, 1976). Kelleher and McCann (1976) consider this seismic gap as due to the greater buoyancy of the material forming the Louisville ridge and carried down by subduction. Nevertheless, it can be noted that the frequency of shallow earthquakes does not decrease along the extension of the Louisville ridge, except opposite the contact of the ridge and the arc in the direction of subduction. The cause of the seismicity gap may thus be related to deformation of the downgoing plate in the ridge–arc contact zone, having as a consequence a strain reduction at the interface of the two plates (Louat and Dupont, 1982). According to this hypothesis, the zone of weak shallow seismicity should follow to the south the arc–Louisville ridge contact during the subduction of the latter. Confirmation or negation of this conclusion must wait a few million years!

5. *Longitudinal Seismological Section of the Tonga–Kermadec*

Both Hanuš and Vaněk (1979) and Louat and Dupont (1982) have presented longitudinal sections showing the distribution of earthquakes in Tonga–Kermadec.

On the simplified section presented by the latter authors, the shortening of the Benioff zone in north Tonga is particularly clearly shown. This corresponds to recent subduction (of 330 km) in this region. Hanuš and Vaněk (1979) figure in their section the influence of relief of the downgoing plate on the morphology of the Benioff zone; thus, opposite the Niue ridge, Louisville ridge (Ozbourn seamount), and the south and north Kermadec seamounts, the present Benioff zone attains depths of only 250, 200, 220, and 250 km, respectively. These shallow depths in regions where focal depths greater than 500 km are found support the concept of the fossil subduction zones (Lau and Horn), prior to the present subduction zone of Tonga and Kermadec proposed by these authors (see Fig. 15).

The effect of relief on the descending plate on subduction remains a difficult problem to resolve. In the present state of knowledge, two models which often have no common link can be compared: on the one hand, well-established relief may cause changes in arc morphology (Dupont, 1982b); on the other hand, there are irregularities in the Benioff zone which can be explained by the subduction of relief whose existence has never been established. Only hypotheses link one with the other. In the case of the Tonga–Kermadec arc system, if for the Louisville ridge it is reasonably certain that there is an elongate structure of which part has been subducted, what can be said of other relief? Is it isolated relief or a chain? The morphology of the Pacific plate makes it impossible to decide with certainty. If the hypothesis of Hanuš and Vaněk can be verified, there will be a means of going back in time and determining whether former relief existed and disappeared.

6. *Conclusion*

The study of the seismicity of the Tonga–Kermadec arc shows that subduction is geographically unstable along active oceanic margins, that subduction in the Tonga–Kermadec arc is not simple—particularly in the north—and that the relative linearity of the arc is unlikely to be a permanent feature of it. The morphology of the Benioff zone can be explained by the anchoring of subducted lithosphere at 700 km, and this plays a important role in the flexure and rupture of the subducted slab with the resultant eastward migration of the trench.

The deep focus earthquakes, where they are coordinated, provide an excellent indication of the geodynamic history of the region; it is by this means that several successive periods of subduction have been discerned. The latest of these modified the north of Tonga where the old limiting subduction–transform fault passes into the Peggy ridge.

Finally, it is worth recalling that the interpretation of seismic data is closely linked to the number and quality of the data (location and focal depth, number of available records).

IV. CONCLUSIONS

Studies carried out over the years on the Tonga–Kermadec ridge have led to an improvement in our knowledge of the area. It can be shown that a knowledge of morphological, refraction, and gravimetric data leads to a better understanding of the general form of the ridge and the superficial and internal structure of this subduction zone, one of the most important structural zones in the South Pacific. The new hypotheses born of the confrontation of new data sought by the scientific community have advanced our ideas on the origin, formation, and evolution of this active margin. We are at but a staging point and research must continue.

It can be stated that the morphology of an island arc is not immutable. An island arc is born, grows, evolves, dies, and becomes fossilized. The morphology not only changes as a result of the volcanic activity which is characteristic of island arcs, with the birth of new volcanoes, rejuvenation of volcanic activity, and the disappearance of volcanic islands by marine erosion, but also through seismic activity through earthquakes with the disappearance or uplifting of parts of an island, or by marine activity with the formation of terraces. Such morphological changes, very common in the Tonga–Kermadec island arc, are all local. In contrast, it appears the subduction of relief present on the subducting oceanic plate may cause, more slowly, morphological changes not detectable on a human time scale and less spectacular than the earlier-mentioned changes, but they are, nevertheless, much more important geographically.

Seismicity permits us, through the study of present-day earthquakes, to go back in time and hypothesize on the mechanisms which operated in the past. The paradox for the nonscientist is that the more earthquakes there are, the more the seismologist is satisfied, for in this way knowledge is improved. It is thus that the study of deep focus earthquakes permits the conclusion that subduction below the Tonga–Kermadec arc is not stable, but is being progressively displaced toward the east. The amount is very small in the Kermadec zone, but is much greater for Tonga—in particular, the northern part where subduction appears to be very recent (3 to 4 Ma). This latter conclusion is supported by intermediate focus earthquakes, or rather by their absence, for there is a seismicity gap in the extreme northern part of the Tonga arc where the Benioff zone only extends down to 330 km.

These regions, which have been called active margins, merit that designation for they are not only active seismically and volcanically but also morphologically. The scientific cruise of the *R/V Lee* in 1982 in the Tonga area, and the projected mission of the *N/O Charcot* in the Lau and Havre basins and over the junction of the arc with the Louisville ridge, can provide new data which may confirm or invalidate the different hypotheses presented here.

The work on the Tonga–Kermadec island arc discussed in this chapter represents only a resumé, an incomplete resumé, for the author was forced to make a selection out of the many papers published. The interested reader is encouraged to plunge into the abundant literature on this area of the southwest Pacific, using the basic list presented here.

V. ADDENDUM

Since the completion of this chapter on the Tonga–Kermadec arc, many new data have been published as a result of the cruises of the *R/V S. P. Lee* (Australia–New Zealand–United States Tripartite Agreement) during March and April 1982, the *R/V Sonne* (West German cruise S035) from December 1984 through February 1985, and the *N/O Jean Charcot* (SEAPSO cruise of GIS, with ORSTOM–IFREMER–UBO–CNRS and BRGM) from December 1985 through January 1986.

The cruise of the *R/V S. P. Lee* (Scholl and Vallier, 1985) provided much new information on the southern part of the Tonga arc platform from single- and multichannel seismic and refraction data, drilling and dredging, accompanied by onshore studies of the Ata and Eua Islands and by studies of the Lau Ridge and Basin. In particular, Morton and Sleep (1985) demonstrated the existence of the top of the magma chamber crustal between 22 and 23°S (Valu Fa Ridge).

The cruise of the *R/V Sonne* provided precision on the trend and morphology of the Valu Fa ridge. Hydrothermal activity on this ridge was demonstrated by Stackelberg *et al.* (1985), and dredging in the northern Lau Basin by the *R/V Thomas Washington* in 1986 brought up sulfur.

Continuing the investigations begun in 1975, French researchers carried out a single-channel seismic and seabeam survey over the southern part of the Tonga Trench and over the zone of contact between the Louisville Ridge and the Tonga arc. These studies also showed the beginning of normal faulting of the Ozbourn guyot. This guyot has been preceded down the subduction zone by another, which still appears in the depths of the trench, and the internal trench wall may be a zone of tectonic erosion (Pontoise *et al.*, 1986).

The Tonga–Kermadec island arc—as well as its backarc basin, the Lau Basin—continues to generate scientific interest. The international scientific community (American, Australian, French, German, Japanese, and New Zealand) tends to combine in small groups, proposing deep drilling within the framework of the Ocean Drilling Program as well as deep dives with American, French, and Japanese submersibles.

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